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Research Paper

Experimental study of solving thermal heterogeneity problem of data center servers

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HIGHLIGHTS

- Increasing server power density increases its surface temperature heterogeneity.
- Variation of servers air flow rates leads to better thermal performance.
- Uniform increase of server's air flow rates enhances thermal performance.
- Proper scheme of servers air flow rates maintains all servers at the low temperature.

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ABSTRACT

Desirable thermal management of data center requires uniform temperature distribution along the servers. Hot air recirculation and cold air bypass in data center leads to non-homogeneous cold air distribution along the servers of the racks which may lead to heterogeneous temperatures distribution along the servers. The present work aims to experimentally study the possibility of controlling these heterogeneous temperature distributions by controlling the cold air flow rates along the servers. A physical scaled data center model was used to conduct this investigation. The effectiveness of thermal management of the servers racks of the data centers has been expressed in terms of intake, rare and surface temperature distributions along the rack servers and the supply and return heat indices (commonly symbolized as SHI and RHI; respectively). Excessive tests were firstly performed under uniform servers fans speed (uniform air flow rates through the different servers). Then the air flow rates distributions along the racks servers has been changed by regulating the server's fans speeds using different schemes of fans speeds regulations at different data centers power densities. It is concluded that a uniform increase of server's flow rate from the bottom to the top of servers rack cabinet provides (i) the lowest temperature at both cooling aisle (around 10%) and exhaust aisles (around 5%), (ii) the best uniform surface temperature of all rack servers (as the standard deviation is reduced from 10 to around 2), and (iii) the best values of thermal management metrics (SHI and RHI) typically SHI is reduced by around 20% while RHI is increased by around 3% to approach the targeted values; 0.1 and 0.9, respectively.

1. Introduction

Huge and high speed data processing needed in a wide variety of human life sectors such as industrial, educational, and administrational services in addition to other private sectors is performed using data centers. These facilities are composed of racks hosing servers with different configurations and/or different capacities. To maintain the efficiency of these servers, proper thermal management is required to keep their operation within targeted temperature values. For this reason great part of power consumed is directed for cooling of these facilities throughout the computer room air conditioning (CRAC) unit (almost 40–50% total power consumed [1]). Under proper thermal management operation about 10–15% of this total energy consumption can be saved [1]. Additional challenge for data center thermal management is how to also maintain the surface temperature of the different servers within the allowable limits [2]. Typical server hardware [2,3] is rated for allowable operating temperature envelope of 35 °C for most data centers with some control; for general applications ASREA has recommended the operating temperature envelope to be from 18 °C to 27 °C. Thus the main scope of data center manufacturer is to remove the hot air exhaust from servers to improve the system cooling efficiency [4].

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Nomenclature

Cp	constant pressure air specific heat (J/kg k)
CRAC	computer room air conditioning
Q	server heat dissipation rate (W)
L	length (m)
$\dot{m}$	air flow rate (kg/s)
N	total number of servers intakes
RHI	return heat index
SHI	supply heat index
T	temperature (°C)
T_{ref}	reference temperature (°C)
U	air velocity (m/s)
X	intake x

Superscripts

C	CRAC
R	rack

Subscripts

i, j	Cartesian direction
In	air inlet to servers
Ti	mean temperature at intake x (°C)
Out	air outlet from server

Different techniques are used for data centers cooling; the most common techniques uses raised-floor configuration where the cooling air is supplied to the data center from the under-floor plenum through perforated tiles (see Fig. 1). The raised-floor arrangement provides unlimited flexibility regarding cooling air flow configurations. The most efficient configuration is the one that depends on separating cold and hot aisles [5,6] to avoid hot air recirculation and cold air bypass. In their study on different data center configurations, Shrivastava et al. [7] found that using raised floor to supply the cold air and extracting the discharge hot air from the ceiling is the efficient data center air distribution system. This flow configuration becomes the standard practice for data center cooling where server racks are commonly arranged in properly oriented-rows to be placed on both sides of the cold aisle. Thus the hot air from neighboring two rows of racks is exhausted into the hot aisle. Then hot air from different hot aisles is collected and returned to CRAC unit. As the server racks have their internal fans, the supplied cooling airflow rate through perforated tiles shall be equal (or greater) than the required airflow rates of these fans to ensure effective cooling process.

Many investigations were performed to provide the best conditions that should provide high cooling efficiency of data centers. Cho et al. [8] studied air distribution in high power density data centers and they concluded that as human thermal comfort is not the aim of data center cooling, supply air velocity is a critical factor in data center. VanGilder and Schmidt [9] studied flow uniformity from data center floor perforated tiles and they reported that 25% perforated tiles opening ratio with 0.61 m plenum depth or more is the optimum for air flow uniformity. In other work, it was reported that reducing system fan speed and increasing air temperature rise across the server increase the energy efficiency in data centers [10,11]. In this case the mean temperature of hot air is raised across the data center room leading to a concern on the system reliability due to approaching the thermal limits of the system.

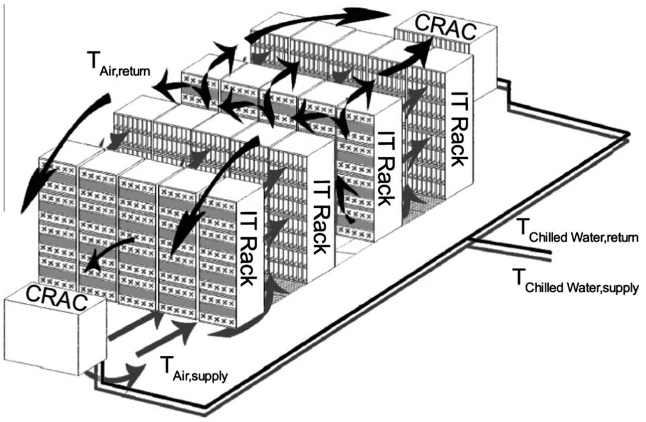


Fig. 1. Typical open aisle data center [4].

Effective data center thermal management can be attained when proper cooling air distribution throughout the room is maintained. In this regard many controlling parameters should be studied; including cooling air flow pattern, temperature distribution inside data center, and server fan air flow rate. The later parameter is interrelated with the server power loading and/or processing load to maintain the server surface temperature within the predefined value as specified by manufacturer or as targeted by standards whichever is more stringent. There are many metrics used for thermal management evaluation in data centers [12–15]. Herrlin [16] concluded that the cooling efficiency of racks depends mainly on the data center room environment, correspondingly the use of performance metrics can help in analyzing these interdependencies.

The most commonly used metrics are those used to evaluate the mixing level between cold and hot air streams in the hot-aisle and cold-aisle arrangement related; namely supply heat index (SHI) and return heat index (RHI). These metrics evaluate the extent of cold and hot air mixing in data center; SHI is the ratio of the heat gained by cold aisle air before entering the racks to the total heat gained by the air in the data center while RHI is the ratio of the heat gained in the air during passing in the rack relative to the total heat gained by the air in the data center. These two metrics have been used by many investigators while studying or attempting to improve data center cooling efficiency [15].

Boucher et al. [17] have experimentally found that racks at the row end exhibit higher temperature than those inside due to hot air recirculation. The study concluded that proper control of CRAC supply temperature, CRAC fan speed, and plenum vent tile openings can greatly improve the energy performance of data centers. Kumar and Joshi [18] found that to overcome the escaping of cold air from the top of cold aisle other methods should be considered rather than the increase of air flow rate through perforated tile which may not be the best way to confirm high efficiency cooling of data center. Cho et al. [19] concluded that the separation of cold and hot air aisles not only minimize the hot air recirculation but also increase the chance of hot air short-circulation over severs especially when the temperature at server backs approaches 35 °C. Patterson [20] reported that cooling system efficiency in data centers strongly depends on flow distribution and air temperature rise across the racks. Durand-Estebe et al. [21] proposed a new temperature adaptive control strategy to minimize the energy need while investigating the effect of increasing server room temperature on the cooling plant energy consumption. Nada et al.

[22,23] presented numerical studies for the thermal performance of data centers under different operating conditions and for different configurations of computer room air conditioning (CRAC) units and physical separations of cold and hot aisles. Temperature distribution, air flow characteristics and thermal management of data centers racks array were predicted and evaluated for the different arrangements.

Most of investigations cited in the literature were experimentally reported in actual data centers or using CFD simulation. Carrying out a research on actual data center is costly and time consuming. To resolve this problems, the similarity analysis was proposed to provide a physically scaled model of real data center [24–26]. Nada et al. [28,27] applied this dimensionless theory to construct a 1/6 scaled physical model test facility simulating the standard data center to improve the thermal management and cooling efficiency of data centers. In their initial study [27], a single rack inside data center room housing four servers was used to find the best conditions providing best thermal management performance. Main conclusions determined optimum conditions to occur at uniform power loading scheme with perforated plate of 25% opening ratio under high power density. The results also showed that there are variations in the servers temperatures along the servers of the rack and along the racks of the racks row due to hot air recirculation and cold air bypass. To prevent hot air recirculation and/or cold air bypass, Nada et al. [28,29] used different arrangements of aisles partitions and containments in data center to control air distribution in a typical data centers using under floor air distribution system for single and multiple racks rows. It was concluded that, using vertical aisle partition above the rack and top containment for aisle enclosure [28] lead to a reduction of the rack inlet temperature by 4–13% and 13–15.5%, respectively, and so the data center cooling efficiency is improved. These results met those stated by Mulay [30] who concluded that the cold aisle containment is not only used to reduce the CRAC power consumption considering dynamic thermal managing of data center, but also leads to better uniform rack inlet temperature. In this regard proper thermal awareness of data center is needed to overcome server overheating or service failure due to inhomogeneous servers' surface temperature distribution [31]. Like-this thermal awareness is realized by using proper management control (scheduling) algorithm to keep discrete server processing speed and/or power load within the allocated values at all times to minimize data center power consumption; including server power and cooling power [31–33]. The scheduling algorithms that minimize the inlet air temperature can minimize the cost of consumed energy as the heat recirculation is reduced [33].

From the literature, researchers and manufacturers shall face the data center problems related to the inhomogeneous temperature distribution over different servers. While reviewing the current published literature, it seems that thermal management of data centers to overcome servers heterogeneous conditions by varying servers fans flow rates was not investigated by previous studies. Even the literature is rich with the dynamic thermal management of data centers and thermal awareness, almost none of these works were concerned with the server's surface temperature to provide proper control strategy on actually programmed servers without scheduling server power load. The current paper is an attempt to resolve these problems by proposing proper thermal management based on the necessity to regulate the cooling air flow rate over different servers along racks such that the servers' surface temperatures become within the designed value. While performing the study, the performance metrics were evaluated to check the effectiveness of the proposed cooling scheme.

2. Experimental facility and procedure

2.1. Scaled data center room

In the current paper, scaled physical model proposed by Nada et al. [27–29] using under floor supply-ceiling return configuration is used to investigate the current investigation of the cooling performance of data center under servers' heterogeneous temperature distribution. A one-sixth geometrical scaled factor and Archimedes number equality were considered in designing and constructing the physical scaled model. A physical scale room simulating data center contained three racks in a row was constructed to conduct the present experimental work. A general layout of the current setup is shown in Fig. 2.

In this setup, a blower is used to supply air to the raised floor. Air enters the model room through perforated tiles located in front of data center racks (cold aisle) to cool the racks servers. After cooling the servers, air was discharged as from the rear of the racks (hot aisle) as a hot air which is then is exhausted from the room top using discharging fans. The room model contains three racks each includes four servers simulating actual racks row in a real data. A group of sixteen T-type thermocouples distributed in the model room are used to measure temperatures of air at racks inlet and outlet as well as servers' surface temperatures. The thermocouples used to measure the inlet and outlet rack air temperatures were installed on a thin plastic chassis in front and behind the middle rack. Four thermocouples are installed on each frame and distributed at different rack heights to measure the inlet and outlet temperature of each server. Two other sets of two thermocouples are located at air inlets to the perforated tile and return fans to measure supply and exit air temperatures to the room. Data Acquisition system and PC are used to record all the temperature readings.

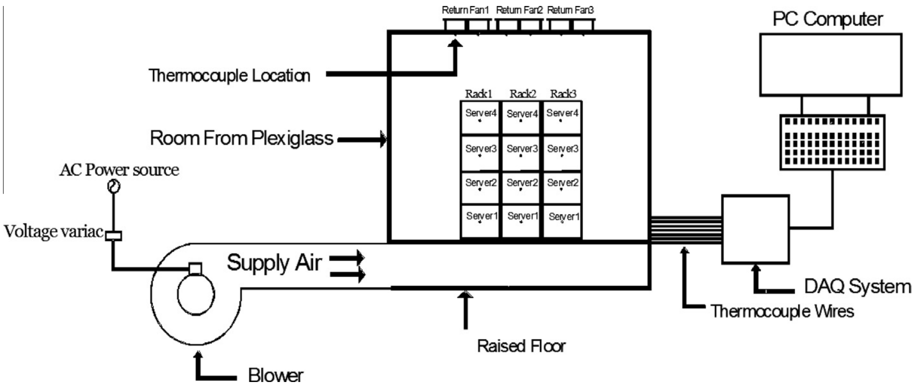


Fig. 2. Schematic diagram of the experimental setup.

The dimension details of the modeled room is shown in Fig. 3. The room walls is made from 1-cm thick Plexiglas sheet and were air tight assembled using silicon. The room outside dimensions is 704.8 (length) × 329.2 (width) × 500 (height) mm with a raised floor height of 100 mm. The cold and hot aisles widths are 101.6 and 75 mm, respectively. The racks dimensions are 101.6 × 152.6 × 332.3 mm (height) designed to accurately simulate actual racks of four servers each [34].

To avoid internal air recirculation, the servers intake and exhaust faces are attached to rack perforated doors. The rack front and rear doors are made of screen mesh of 65% opening ratio to simulate actual servers [35]. A variable speed fan (0.45 m^3/min) and electric heater (150 W) are used in each server cabinet to simulate the fan and heat generation of actual servers. The server fan flow rate is controlled by controlling the input power supplied to the fan using a variac. Hot wire anemometer is used to measure the fans flow. A nickel-chromium wire wrapped around mica plate and covered by a 0.5 mm in thick stainless steel plate is used to generate heat in each server as shown in Fig. 4. A variac is used to control the input power to the server.

2.2. Data reduction and experimental procedure

The measured temperature distributions throughout the modeled data center room have been used to evaluate the efficiency of data center cooling under specific operating conditions. Due to the occurrence of hot air recirculation and cold air bypass (infiltration) phenomena, the intake air a rack is expected to be a mixture of cold supply and recalculated hot air and this cause an increase in the intake air temperature. It has been noticed that about 40% of the supplied cold air passes through the racks servers and the rest is bypassed around the racks [36]. The efficiency of data center thermal management is calculated from the measured temperature distributions in terms of thermal metrics proposed by Sharma et al. [14] to determine SHI and RHI as follows:

$$SHI = \left(\frac{\delta Q}{Q + \delta Q}\right) = \frac{\text{Enthalpy rise in cold aisle before entring the server}}{\text{Total enthalpy rise of the cold air}} \quad (1)$$

$$RHI = \left(\frac{Q}{Q + \delta Q}\right) = \frac{\text{Total heat extraction by the CRAC units}}{\text{Total Enthalpy rise of the cold air}} \quad (2)$$

where Q is the total heat dissipation from all the racks in the data center and δQ is the enthalpy rise of the cold air before entering the racks. From temperature measurements performed along single rack, the enthalpy rise and heat dissipation are computed from temperature measurements by:

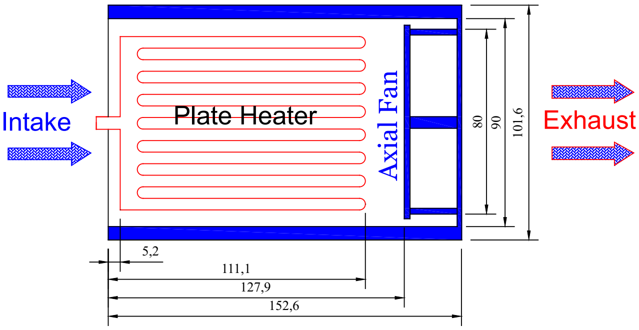


Fig. 4. Top view of the server (dimensions in millimeters).

$$Q = \sum m^r Cp(T^r_{out} - T^r_{in}) \quad (3)$$

$$\delta Q = \sum m^r Cp(T^r_{in} - T_{ref}) \quad (4)$$

where m^r is the mass flow of air through the rack, T^r_{in} and T^r_{out} are the average inlet and outlet temperature from the rack and T_{ref} is the vent tile inlet air temperature. Neglect heat transfer in the plenum and constant temperature of the air exit from the vent tile the performance metrics can be evaluated using the following relations:

$$SHI = \left(\frac{\sum(T^r_{in} - T_{ref})}{\sum(T^r_{out} - T_{ref})}\right) \quad (5)$$

$$RHI = \left(\frac{\sum(T^r_{out} - T_{in})}{\sum(T^r_{out} - T_{ref})}\right) \quad (6)$$

It is easy to observe that:

$$SHI + RHI = 1 \quad (7)$$

Eqs. (1) and (4) show that increasing δQ cause an increase in (T^r_{in}) and SHI. Rising (T^r_{in}) may leads to systems failure and reliability problems. Increasing (T^r_{in}) also causes entropy generation decreasing energy efficiency. Therefore, SHI may be used as an indication of thermal management and energy efficiency in data center. A low RHI indicates bypass of the cold air and its mixing with the rack exhaust air without passing on the servers. Ideal values of (SHI and RHI) are (0 and 1) while typical benchmark acceptable ranges of SHI and RHI are SHI < 0.2 and RHI > 0.8 [14].

The experimental procedure followed throughout this study includes the following steps:

1. Initially confirm the clean and accessible of data center room.
2. Check and set for operation the blower and its speed at the predefined values according to the experimental program.

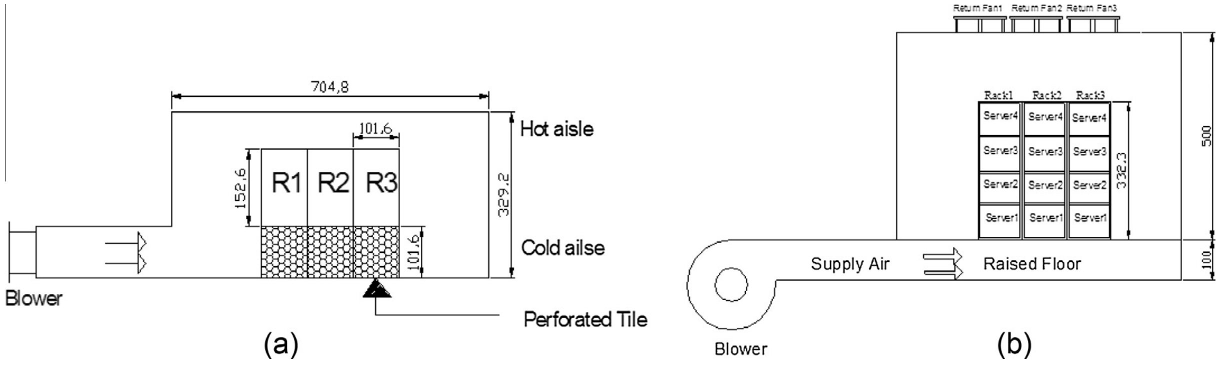


Fig. 3. Scale model data center (a) top view and (b) side view (dimensions in millimeters).

3. Adjust the servers supplied power according to the program.
4. Adjust the fan speed according to the experiment objective.
5. Turn on the data acquisition system to collect all temperature measurements.
6. Wait ad ensure achievement of steady state.
7. Record all instruments readings (temperatures, air flow rate, voltage, and current).
8. Repeat steps 3–7 at different power densities for the middle rack at each studied case.

2.3. Experimental program

Firstly group of experiments have been performed at homogenous power scheme to check the existence of heterogeneous temperature distribution regarding server's surface temperature along the rack at different room power densities. As the objective of the current study is to propose the optimum thermal management procedure to remove/reduce the heterogeneity of temperature distributions over servers' surfaces, the controlling variables of the experimental program include (i) the variation of power density under homogeneous cooling air flow rates, and (ii) the use of different schemes based on different server's cooling air flow rates. The effect of these two factors are investigated while other parameters of data center are kept constant; see Table 1 for more details. It is important to state that the blower air flow rate is synchronized with the racks power density to ensure that server's temperatures are within the recommended range as in real data centers. To ensure measurements consistency, each experiment is repeated at least twice. The measurements included air temperatures, air flow rate, voltage and current. The uncertainties in measuring these quantities were estimated to be ±0.2 °C, ±2%, ±0.25% and ±0.25%, respectively.

3. Results and discussion

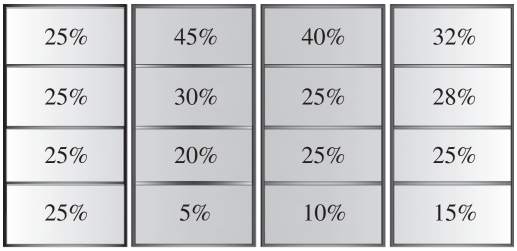
The first group of experiments were performed under conditions of homogenous power density with homogenous cooling air flowrates over the four servers along the test rack - abbreviated as Case (1). Then the cooling load over different servers has been scattered with the purpose of approaching uniform servers' surface temperature abbreviated to be Case (2), Case (3), and Case (4). To properly show the influence of any proposed cooling load scheme on the modeled data center thermal analysis both groups (all the four cases) of experiments have been plotted on the same relevant figures. As shown from Figs. 5–7, the use of homogenous cooling loads leads to almost uniform temperature distribution at the rack inlets with slight increase in the servers' front temperature due to the influence of heat generation servers on its surrounding (within 1 °C). At rear of servers, the temperature is increased owing to heat transferred from servers with nearly ascending order as the exhaust gases receive more energy along the rack except at the top server where the influence of cooling air bypass leads to slight decrease in the exhaust air temperature. This behavior is independent of data center room power density, as the overall cooling load is synchronized with the room power density to maintain the servers, surface temperatures within the allowable operating range (correspondingly the exhaust air temperature is nearly kept constant).

From the first view, it can be decided the non-necessity of additional thermal management as a suitable degree of homogenous temperature distributions are observed. But when inspecting the servers' surface temperature (the main target to keep the high processing efficiency of data centers) for uniform cooling flowrates (Case (1)) shown in Figs. 8–10, a significant ascending temperature rise along the rack from bottom to top is observed. This result is mainly due to the accumulation of energy absorbed by cooling air as the exhaust is directed from bottom to the exhaust fan. This temperature rise varies according to the power density in the range of around 60–80 °C for the bottom server and varies from around 85 to 135 °C for the top server. This is why Nada et al. [28,27] proposed for better thermal management of data centers the use of servers having highest processing duties at the bottom to keep its surface temperature and so its effectiveness at optimal values no matter the room power density. This discrepancy in servers' surface temperature is known as heterogeneous temperature distribution which may lead to the overheating of local servers even the exhaust air temperatures are kept within the designed value.

In purpose of keeping surface temperatures of all servers within narrow range of discrepancy, additional thermal management procedure based on the cooling load of servers along the rack is proposed. In this regard, four mentioned schemes are studied to recommend the best one of them that would keep all servers almost at the same temperature while maintain a high degree of temperature distribution at both front and rear of racks. In fact any of these schemes can be realized as the most of servers' house fans are currently programmable, and so fan power supply can be varied according to the server location along the rack. The first choice was to remove both effects of bypass cooling and accumulation of energy in exhaust air occur at the top server, so most of

Table 1
Details of experimental program.

Ranges of controlling variable	Measured/studied variables
1. Room power density (W/m^2): 379, 759 and 1139 2. Schemes of server's cooling flowrate: a. Uniform air cooling flowrates, 25% of the air flow rate to each server (Case (1)) b. Non-uniform air flowrates specified for Case (2) c. Non-uniform air flowrates specified for Case (3) d. Non-uniform air flowrates specified for Case (4)	1. Temperature distribution throughout data center room 2. Servers' surface temperature 3. Supply/return heat indices (SHI & RHI)



Case (1)	Case (2)	Case (3)	Case (4)
25%	45%	40%	32%
25%	30%	25%	28%
25%	20%	25%	25%
25%	5%	10%	15%

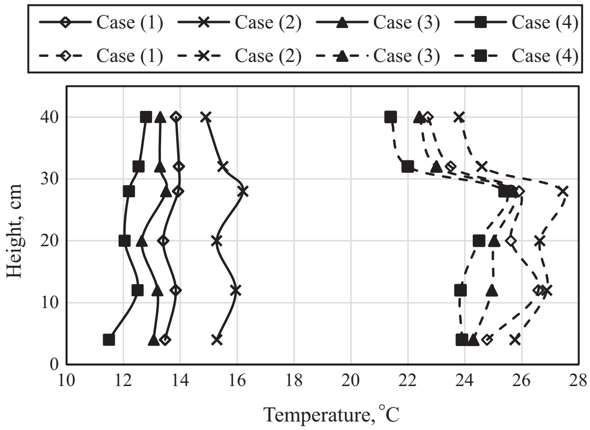


Fig. 5. Temperature profile at front (solid lines) and at rear (dashed lines) of the rack at room power density of 379 W/m^2.

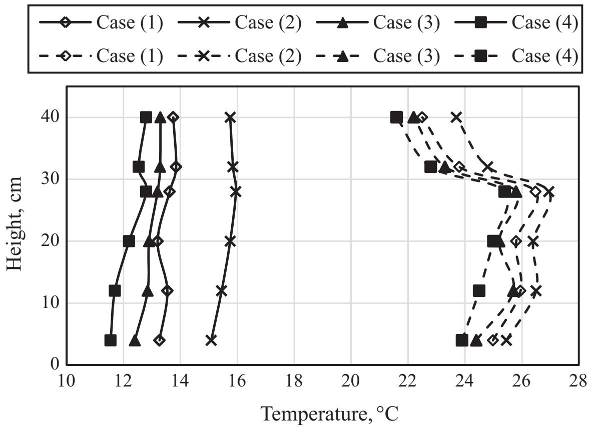


Fig. 6. Temperature profile at front (solid lines) and at rear (dashed lines) of the rack at room power density of 759 W/m^2.

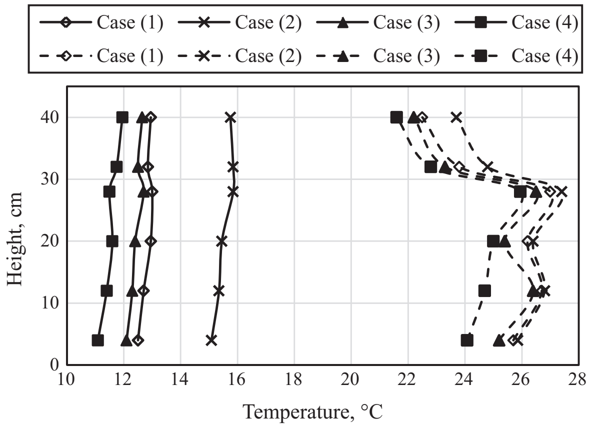


Fig. 7. Temperature profile at front (solid lines) and at rear (dashed lines) of the rack at room power density of 1139 W/m^2.

cooling air is directed to that server; Case (2). Due to the blockage of cooling air at low level servers, these servers are heated more and affect their surroundings, so both temperatures of inlet and exit of low level servers are increased (see Figs. 5–10). In comparison with the homogeneous scheme, the inlet air temperature is increased over 15% and the exhaust air temperature is increased by around 3%. For Case (2), the mass flowrate over the top server

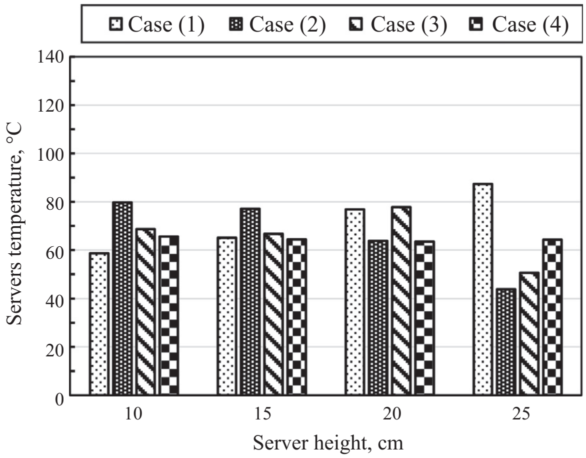


Fig. 8. Variation of servers' temperature along rack height for different scheme of server cooling at room power density of 379 W/m^2.

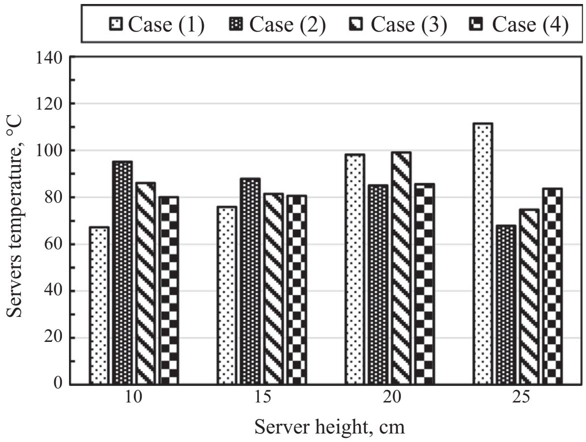


Fig. 9. Variation of servers' temperature along rack height for different scheme of server cooling at room power density of 759 W/m^2.

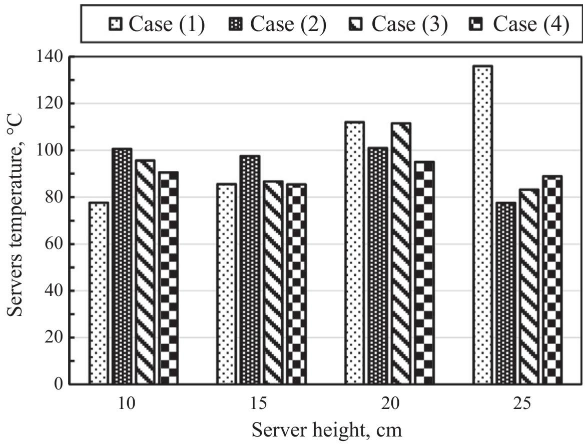


Fig. 10. Variation of servers' temperature along rack height for different scheme of server cooling at room power density of 1139 W/m^2.

is high for fixed power density enhances the server cooling causing the server temperature to be the lowest. This scheme to cool the data center leads to the descending temperature rise of the servers' surface temperature which should oppose the natural convection of heat transfer, correspondingly this scheme is not recommended and other schemes are studied. The third scheme was proposed as the middle servers were observed to have almost the same temperature at rear of the rack, so equal air cooling flowrates are used; Case (3).

The use of Case (3) reduces the blockage of cooling behind the front of the rack, so air is slightly heated but with level lower than the previous cases (Case (1) and Case (2)). In comparison with the homogeneous scheme, the inlet air temperature is slightly reduced by around 4% and the exhaust air temperature is slightly reduced by around 2%. Correspondingly the absorbed heat provides exhaust air at rack rear with lower temperature no matter the applicable room power density (see Figs. 5–7). Under scheme of Case (3), even the servers' surface temperatures of the bottom two servers are almost equal especially at low power density, the top is still the lowest while the third one possesses the highest temperature value (see Figs. 8–10). So additional lowering for cooling air of the top server is needed with slight increase of the third one in comparison with the second to compensate the effect of buoyancy. Accordingly, the final fourth scheme is proposed (Case (4)).

Case (4) exhibits the best temperature distributions among other studied cases as shown in Figs. 5–7. As the cooling air is uniformly sucked by the server fans with almost no blockage, the increase of the cold aisle temperature (due to the effect of hot servers on their surroundings) is the lowest, correspondingly the exhaust air temperature is also the lowest (as the overall cooling load is fixed) under all studied room power densities. In comparison with the homogeneous scheme, the inlet air temperature is reduced by around 10% and the exhaust air temperature is also reduced by around 5%. From Figs. 8–10, it is observed that the surface temperatures of all servers are approximately equals due to the proper distribution of cooling air flowrates. The average surface temperature of all servers along the rack, and the corresponding standard of deviation (to estimate the degree of discrepancy between local and mean values) are determined and plotted in Fig. 11. It can be observed following results:

i. The mean temperature value is increased by the increase of the power density.
ii. Under uniform cooling flowrates, the standard deviation is the maximum among studied cases for all studied power densities.
iii. All the studied cases lead to reduction in the average temperature but with different standard of deviation.
iv. Case (4) provides not only the lowest average temperature but also with minor standard of deviation indicating almost equal temperatures of all servers along the rack.

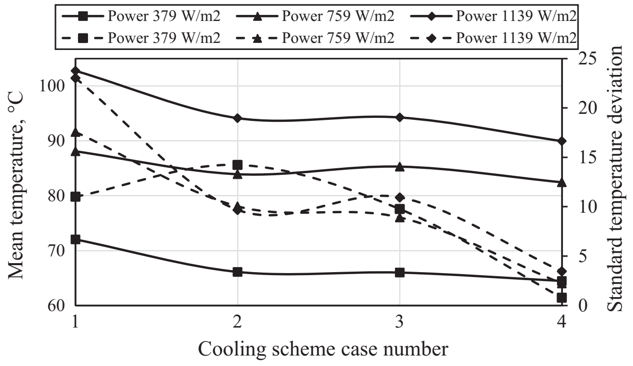


Fig. 11. The variation of the mean temperature along the rack (solid lines) and the corresponding standard of variation (dashed lines) at the four studied cooling schemes.

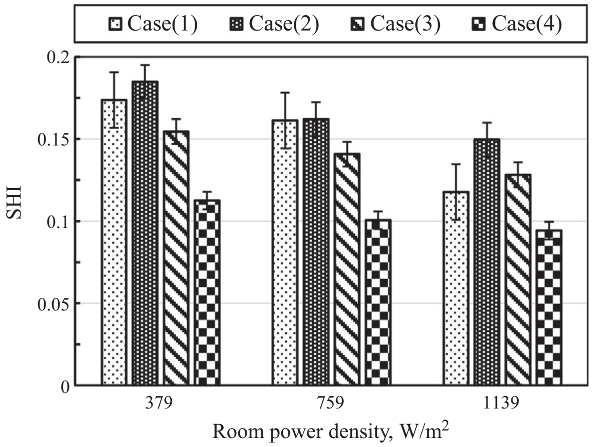


Fig. 12. Variation of supply heat index (SHI) with data center room power density for all studied cooling schemes.

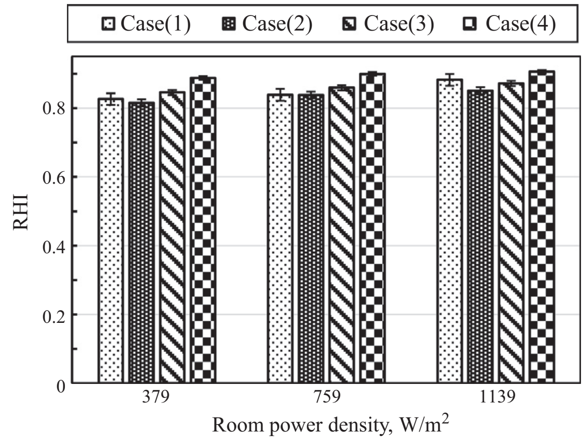


Fig. 13. Variation of return heat index (RHI) with data center room power density for all studied cooling schemes.

To test the economy of cooling system of data center, the performance metrics are determined; supply heat index (SHI) and return heat index (RHI). The recommended values of SHI is to be lower than 0.2 while that of RHI should be higher than 0.8. The computed values for SHI and RHI for all studied cases are shown in Figs. 12 and 13, respectively. It can be noticed that, Case (2) provides the worst data center thermal performance. The data are shown with the error bar for the standard deviation which is reduced at higher power densities. For Case (4) in comparison with the homogeneous scheme; Case (1), the SHI is typically reduced by around 20% while RHI is increased by around 3% to approach the targeted values; 0.1 and 0.9, respectively. Correspondingly, Case (4) provides the best performance where SHI is the lowest (approaches 0.1) and RHI is the maximum (approaches 0.9).

4. Comparison with pervious experimental and CFD data of real data centers

To validate the present work, the results of the present work are compared the results of the available previous experimental and CFD works conducted on real data centers at uniform air servers flow rates (Case (1)). No previous experimental data are available for other cases to compare with it. Figs. 14 and 15 show the comparisons for the front and rear racks temperatures and for the SHI and RHI of the present work with those of the experimental work

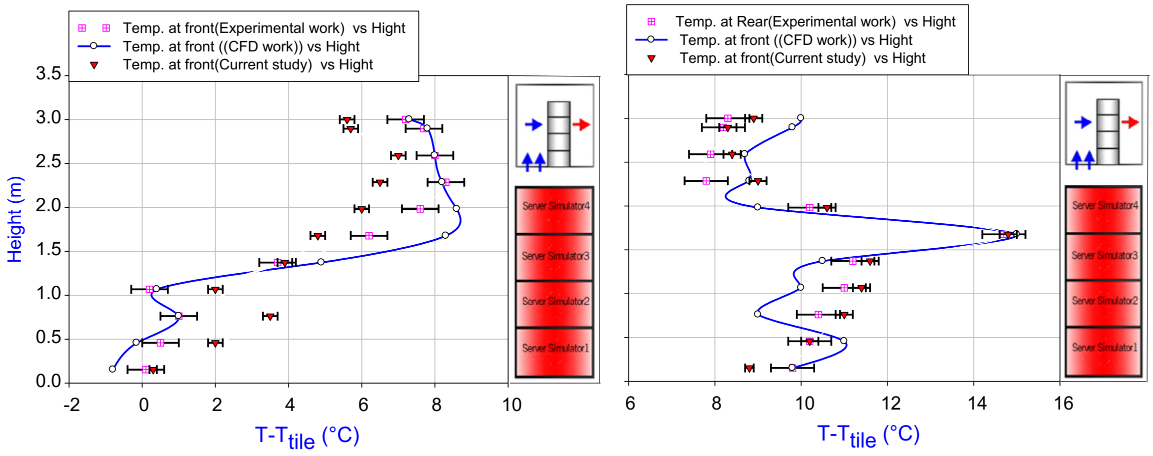


Fig. 14. Comparison of the temperature profiles in front and rear for the rack with pervious experimental work [34] and CFD work [23].

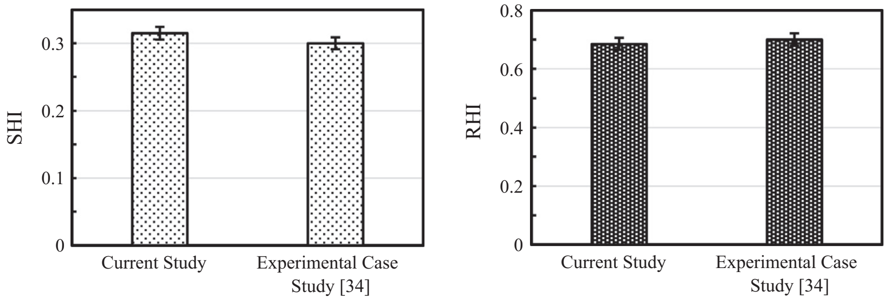


Fig. 15. Comparison of supply heat index and return heat index of Case (1) of the current woke with pervious experimental work [34].

by Smith et al. [34] and CFD work by Nada et al. [23], respectively. The figures reveal good agreement for the SHI and RHI and fair agreement for the temperature distribution. The deviation in the temperature distribution can be attributed scaling of the physical model where 100% of similarity with the real data center cannot be attained [28].

5. Conclusions

In this paper, the effects of power density and different cooling schemes of servers along the rack on temperatures profile, server's surface temperature and thermal management metrics have been studied based on physically scaled data center model. Based on the dimensionless analyses, a scaled test facility comprising of data center room with three racks accommodating four servers has been designed and constructed. Efficiency of data center thermal management can be improved by the proper servers cooling schemes to keep all servers almost at the same lowest applicable temperature. From the current study, the following results can be stated:

- The increase of data center power density leads to the increase of servers' surface temperature such that the surface temperature of discrete servers increases along the rack.
- The heterogeneous temperature of servers provides the improper thermal management of the data center and so consumption of more energy.
- The variation of cooling flowrates leads to better data center thermal performance.
- The uniform increase of server's flowrates from the bottom to the top of servers rack cabinet provides (i) the lowest temperature at both cooling aisle (around 10%) and exhaust aisles (around 5%), (ii) the best uniform surface temperature of all rack servers (as the standard deviation is reduced from 10 to around 2), and (iii) the best values of thermal management metrics (SHI and RHI) typically SHI is reduced by around 20% while RHI is increased by around 3% to approach the targeted values; 0.1 and 0.9, respectively.
- Using proper scheme of air cooling flowrates can lead not only to highest efficiency but also to maintain all servers at the same low temperature.

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